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TECHNICAL NOTE

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STATISTICS OF SOLAR COSMIC RAYS AS INFERRED FROM CORRELATION WITH INTENSE GEOMAGNETIC STORMS

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SUMMARY

A statistical study has revealed that solar cosmic rays occur in a nonrandom fashion in the proximity of the earth. These solar cosmic ray events show a tendency to occur in sequences and to occur more frequently in spring and fall. These results are inferred from data pertaining to geomagnetic storms having intensities exceeding a certain threshold. This threshold was chosen to provide the best correlation with direct indicators of solar cosmic rays such as riometry and high-altitude balloon measurements. The desirability of using geomagnetic data for statistical analysis lies, of course, in such data being available over many years.

INTRODUCTION

One of the most interesting of the scientific findings resulting from the early flights of the Explorer satellites was the existence of two radiation belts encircling the earth's magnetic axis. Thus, at an early stage of space exploration, it was recognized that particle radiations would constitute a hazard to manned space flight and suitable safeguards would be needed. Shortly thereafter it was discovered that solar flares, in addition to producing a plasma cloud which causes geomagnetic storms, also produced a stream of energetic protons. (See ref. 1.) The energies of these protons range into hundreds of Mev, or even in certain instances, into the Bev range. These so-called solar cosmic ray particles constitute a much greater hazard than the energetic particles which populate radiation belts. To shield adequately against these solar cosmic rays poses a formidable design problem and imposes very restrictive constraints on our capability of carrying out manned lunar and deep space missions. Shielding requirements will clearly be reduced if criteria enabling some degree of prediction can be developed or alternatively if more can be learned about the statistics of occurrence of solar flare events so that the most favorable periods of launch could be selected in advance. The first avenue of approach has been followed by Anderson (ref. 2). Moreover, the work of Bell (ref. 3) and others, although not specifically directed at this problem, might materially aid in developing effective prediction criteria. Such researches may be described as following a synoptic approach (in analogy with synoptic meteorology) in which predictions are based on the actual appearance of the solar disk. The statistical approach, on the other hand, might be likened to that area of meteorology which is concerned with establishing long-term averages in climate at specified geographical locations, such information being of importance to bridge designers, hydrologists, and so forth. It is this approach which is adopted in this report. An attempt has been made to determine general statistical features of the solar-induced "weather" in the vicinity of the earth-moon system. Direct detection of solar cosmic rays is provided by riometry measurements and by using ionization counters flown in high-altitude balloons. Unfortunately, there is not enough of such data to provide an adequate basis for a statistical analysis. To remedy this situation an attempt has been made to establish a correlation between riometry and the data obtained from balloons on the one hand and the more intense geomagnetic storms on the other. The correlation is believed to be sufficiently encouraging to justify the use of geomagnetic data, of which there is a great deal, to define these broad statistical trends of solar cosmic ray events in which our interest is centered.

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SYMBOLS

A_p	average of a_p over 24 hours
a_p	3-hourly planetary index
C_b	corrective coefficient for bunching
$\bar{C}_b$	approximate rounded-off value for C_b
$C_{s,f}$	corrective seasonal factor for favorable launch
$C_{s,u}$	corrective seasonal factor for unfavorable launch
D	index denoting number of days
K	index denoting number of events
P	probability of an event occurring

P_K probability of K events occurring

σ standard deviation

GENERAL DISCUSSION OF SOLAR PHENOMENA

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The sun's magnetic field (ref. 4) may be thought to resemble a distorted dipole at distances not too close to the sun. The manner by which this distortion is brought about is illustrated in figure 1. By starting with a dipole field (fig. 1(a)), the sun being a hot conducting plasma, the lines of force are firmly anchored to the surface (slippage is forbidden) and the dipole field must participate in the sun's rotation (ref. 5). However, there is plasma continuously streaming from the entire surface of the sun. As a volume element of the plasma moves away from the solar surface, conservation of angular momentum would tend to decrease its angular velocity. However, no significant relative velocity between the plasma and the rotating solar magnetic field can develop because of the high plasma conductivity. The plasma volume elements are thus rotated and experience a centrifugal force. In addition, the plasma drags magnetic lines out of the sun itself. These lines behave like elastic strings and will apply a small radially inward force. There is, therefore, a resultant force tending to draw the plasma into the sun's equatorial plane. In the light of these considerations, it is deduced that the dipole field becomes distorted as shown as figure 1(c).

From time to time intense flares appear on the sun's surface in heliocentric latitudes generally between 10° and 30°. Their mechanism of origin is far from thoroughly understood. However, it is known that they are accompanied by ejection of a proton stream which reaches the earth's orbital radius in about half an hour and by emission of a plasma cloud which reaches the earth's orbital radius in about 24 hours. Both the proton stream and plasma cloud will tend to follow magnetic lines associated with the sun's distorted dipole field. (See fig. 1(d).) As a result, there is good reason to believe that, when one engulfs the earth, the other will also. This belief is borne out by the analysis subsequently presented and deduction of certain broad statistical features pertaining to proton streams (solar cosmic rays) on the basis of an analysis of the more intense geomagnetic storms appears to be justified. In particular, it is believed they are subject to a seasonal variation. Such a seasonal variation is to be expected in the light of the theoretical picture already drawn of the sun's distorted dipole field having a disk-like structure. Thus, as the earth moves in an orbital plane which is inclined to this disk, such a seasonal variation would follow.

In figure 2 (from ref. 6) is presented a plot of solar activity (as determined from sunspot counts) over the past 200 years. It will be noted that superimposed on the well-known eleven-year periodicity there is a periodicity of about 90 years. This longer periodicity has a roughly sawtoothed shape as indicated by the dotted curve drawn through successive maxima in figure 2. The past solar maximum seems to be just at the tip of one of the sawteeth and there are some who contend that the next maximum in 1968-1969, will be substantially less than the one just past. (See refs. 7 and 8.) Indeed there are indications that the past cycle has been particularly erratic which might well suggest an incipient instability preceding a major change in level of solar activity. This should not, of course, be relied on.

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SOLAR-INDUCED TERRESTRIAL EFFECTS

For a long time it has been known that sunspot activity on the sun's surface induces transient effects in the earth's environment. Although little was known concerning the mechanism of interaction, irrefutable proof of such interaction was provided by the observed 11-year periodicity in magnetic storm activity and the 11-year periodicity in the width of the rings of redwood trees (implying a corresponding periodicity in climatic conditions) both in phase with the 11-year sunspot cycle. It was further supposed that the dominant influences of the terrestrial environment were associated with solar-flare outbursts. As a result of the intensified research into solar phenomena and solar terrestrial relations during and subsequent to the International Geophysical Year (IGY), a beginning has been made of fitting the pieces together and establishing the general pattern of such events. A typical sequence of terrestrial events associated with a solar cosmic ray event induced by a flare is shown in figure 3 taken from reference 2. The flare results in a significant increase in electromagnetic radiations in the far ultraviolet and X-ray portion of the spectrum. Such radiation increases ionization in the ionospheric shells on the sunlit side of the earth, giving rise to a so-called sudden ionospheric disturbance (SID) and, by virtue of some form of dynamo action, to slight perturbations in the earth's magnetic field, that is, so-called magnetic crochets. These effects endure for the period during which the flare is visible. Between 1/2 hour and 2 hours after flare onset, the earth is bombarded by solar cosmic rays consisting almost entirely of protons having energies up to hundreds of Mev. Such particles are able to penetrate to the upper reaches of the earth's atmosphere in the vicinity of the earth's magnetic poles where there exist windows in the earth's magnetic dipole field and produce intensification of the ionization in these regions. As a result there is a fall off in received galactic radio noise because of the increased absorption. A day or so later the earth is engulfed by a plasma cloud. This cloud gives rise to geomagnetic and ionospheric storms, aurora, and reduction in intensity of galactic cosmic rays (so-called Forbush decreases).

CORRELATION BETWEEN SOLAR COSMIC RAY EVENTS AND INTENSE GEOMAGNETIC STORMS

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It is the solar cosmic ray component which poses the hazard to space flight and hence it is in the statistical characteristics of these components that our interest lies. It is natural then to turn first to direct measures of solar cosmic rays to provide such statistics.

Riometry (radio ionospheric opacity measurements) provides a direct measure of such effects. In addition, solar protons are directly detected by using ionization chambers and particle counters flown on balloons at high latitudes. Unfortunately, there is not enough of these data to provide an adequate basis for statistical evaluation. In view of the tendency of geomagnetic storms and solar cosmic ray events to be associated with one another - an association which is not inconsistent with current theories propounded in reference 9 in which both the motion of the proton stream and the plasma cloud are constrained to follow the distorted solar dipole field - it seemed worthwhile to investigate the degree of correlation between geomagnetic data on the one hand, and riometry and data obtained by using high-altitude balloons on the other. If such a correlation could be established, then, of course, it permits one to use extensive geomagnetic storm data to evaluate the statistics of solar cosmic rays. The totality of data used in establishing the correlation is presented in figure 4.

Data Obtained By Using High-Altitude Balloons

In the center strip of figure 4 are indicated "significant" cosmic ray events as defined by the balloon data of Winckler (ref. 1). These so-called "significant" events vary widely in intensity and, as Winckler has done, they are broken down into two broad classes: weak events represented by the open symbols, and strong events represented by the solid symbols.

Riometry Data

Riometric measurements define the reduction in galactic cosmic radio noise expressed in decibels. It was desirable to select a threshold sufficiently high to eliminate all of the insignificant extraneous effects and yet sufficiently low to embrace as many of the significant balloon events as possible. With this in mind, a threshold of 4 decibels was selected in this case.

Those events for which the riometer reading was greater than 4 decibels are denoted by the lower line segments in figure 4. The length of the line segments defines the riometer reading. In certain cases the effect was so intense that the riometer went off scale (>15 decibels) and in these cases arrowheads have been attached to the line segments.

Geomagnetic Data

An over-all measure of geomagnetic activity is provided by the whole day A_p index. This index is obtained as follows. At each of 11 observation stations, the fluctuations in each of the three magnetic components are observed over 3-hourly intervals. The greatest of these fluctuations is divided by 2 (thus the effective amplitude of the fluctuation is given) and expressed in gammas. The mean of these 3-hourly amplitudes for all 11 observation stations defines the 3-hourly planetary index a_p. These are in turn averaged over 24 hours to give the A_p index.

Geomagnetic storms may be subdivided into two main groups:

(1) Intense nonrecurrent geomagnetic storms associated with flare outbursts.

(2) Less intense recurrent geomagnetic storms associated with M regions (currently believed to be solar active regions passing close to the center of the solar disk).

In choosing a threshold for geomagnetic storms, it is clearly desirable to keep it sufficiently high to eliminate the recurring storms and yet sufficiently low to embrace the significant balloon events. With these considerations in mind the threshold was set at $A_p = 80$. Geomagnetic storms having $A_p > 80$ are represented by the upper line segments in figure 4, the length of the line segments defining the A_p associated with each such storm.

General Discussion of Correlation

It will be noted from figure 4 that, with but few exceptions, arrival of solar protons is accompanied (with relatively minor time lag) by a geomagnetic storm. The reverse, however, is not the case. This is to be expected on the grounds that the slower moving plasma cloud will be subject to substantially greater lateral spread than the proton stream and the earth must on occasion be engulfed by the plasma cloud and yet missed by the proton stream.

Bearing these considerations in mind, on the whole the correlation appears to be sufficiently encouraging to justify the use of the geomagnetic data to establish the broad statistical features of the incidence of solar cosmic rays.

An attempt to carry the analysis a step further and actually distinguish between weak, moderate, and strong events on the basis of numerical measure of A_p proved unsuccessful with the data available.

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STATISTICAL ANALYSIS OF SOLAR-INDUCED EVENTS

Occurrence of Intense Geomagnetic Storms

Geomagnetic storms for which $A_p > 80$ are shown in figure 5 for the period 1940 to 1960. Storm data for the years preceding 1940 have not been included since it is not available in terms of A_p.

In figure 6 the same data are presented in the form of a polar plot. The concentric circles correspond to each of the years 1943 to 1960. The sectors reading counterclockwise define the months of the year. Two statistical features are noticeable in this polar plot. One is the tendency for events to occur in sequences, the so-called "bunching" effect. The other is the "seasonal effect" or a propensity (ref. 10) for events to occur when the earth in its motion about the sun is at its furthest distance from the sun's equatorial plane. The question might be raised as to why flare events tend to occur when the earth is farthest removed from the equatorial plane of the sun. It is conjectured in reference 10 that as illustrated in figure 1(d) the fringes of the disk are the more disturbed rather than the interior of the disk, which is relatively quiet. Hence, it may be expected that solar-induced disturbances will be especially prevalent when the earth is in one of the turbulent fringe regions. Note points P_2 and P_4 in figure 7.

An attempt has been made to incorporate these statistical features in probability estimates by introducing corrective coefficients for bunching and seasonal variation. Implicit in this approach is that these two effects be independent and can therefore be considered separately. This is certainly justified in this first analysis. Another point which should be made at the outset is that the statistics obtained from the analysis of geomagnetic data cover all significant events both weak and strong as observed from balloons. It is assumed, however, that the same statistics apply to both weak and strong events individually. It is believed that the distinction between weak and strong solar events is simply one of intensity and the mechanism of their production is essentially the same. Such being the case it is felt that the statistical features are unlikely to be markedly influenced by the intensity of the event in question.

A discussion of probabilities and the manner in which they are modified by the bunching effects and the seasonal variation will now be given.

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Probabilities Based on Random Distribution

If the probability of encountering a solar event is P per day, then the probability of encountering K such events in a period of D days (assuming purely random distribution) is given by the binominal expression:

$$P_K = \frac{D!}{K!(D - K)!} P^K(1 - P)^{D-K}$$

Under conditions which are satisfied in the present instance, this expression can be approximated by the Poisson law as

$$P_K = \frac{(DP)^K}{K!} e^{-DP}$$

By using the Poisson expressions the probability of encountering one or more events has been obtained and the sum has been plotted in figure 8 as a function of spaceflight duration by using as a parameter the number of events occurring on the average per year.

Corrective Factor for Coupling of Events

The tendency for events to occur in sequences will tend to lower the probability of encountering a single event. At the same time such bunching will raise the probability of encountering two or more events. Due allowance has been made for such effects by introducing a corrective coefficient for bunching $\overline{C}_b$. This coefficient has been evaluated in the following way. For any particular year an actual count has been made of the number of days on which, if a spaceflight of specified number of days duration had been initiated, one or more events would have been encountered. Divided by the number of days in the year this value will give the actual probabilities of encountering one or more events for the year under consideration and for the specified flight duration. A yearly corrective coefficient C_b is now defined as follows:

$$C_b = \frac{\text{Actual probability (evaluated as above)}}{\text{Theoretical probability (completely random distribution of the events in the year in question being assumed)}}$$

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These corrective coefficients are presented in table I for three mission times of 5 days, 10 days, and 15 days. Wherever blanks appear in this table it implies that fewer than six events occurred in the year in question and a statistically meaningful evaluation of C_b could not be made. It will be noticed that the C_b values averaged over the period 1943 to 1960 are very insensitive to flight duration for the durations of current interest. Clearly it suffices to use a rounded-off value of $\overline{C}_b$ of 0.8 as a corrective factor for bunching. Probabilities modified by this factor are presented in figure 9(a).

A similar calculation has been made for two or more events. In view of the insensitivity to flight duration, it has been evaluated only for a 10-day mission. The results are also presented in table I. In view of the relatively large scatter (large σ) one would appear to be justified in using a corrective factor of 2 in this instance.

Corrective Factor for Seasonal Variation

By referring to figure 6 it will be noted that solar events are particularly frequent during two 2-month intervals when the earth is at its furthest distance from the sun's equatorial plane. By counting the number of events during these periods of unfavorable launch and expressing this as a ratio to the number of events that would have fallen in these sectors, completely random distribution of points being assumed, the seasonal corrective factor $C_{s,u}$ corresponding to launch during these unfavorable months is obtained. In the same way a seasonal corrective factor for periods of favorable launch $C_{s,f}$ has been obtained. The results are presented in table II. Probability plots amended by these seasonal corrective factors are presented in figure 9(b).

Finally in figure 9(c), plots have been made of probabilities in which due allowance is made for both bunching and seasonal variation. If, for example, a 14-day mission were planned in one of the periods of favorable launch (fig. 6) and if 8 solar cosmic ray events were expected, then from figure 8 the probability of a solar cosmic ray event would be 0.2648 if the events were random; from figure 9(a) the probability would be 0.2118 if the bunching effect is considered; from figure 9(b) the probability would be 0.1721 if the seasonal effect is considered; and finally, from figure 9(c) the probability would be 0.1377 if both effects are considered.

CONCLUDING REMARKS

It is believed that the correlation between significant solar cosmic L
ray events and those geomagnetic storms for which the magnetic index A_p 1
is greater than 80 is sufficiently definitive to justify the belief that 6
the broader statistical features will be the same for both. On this 5
basis it is to be expected that cosmic ray events in the earth's vicin- 9
ity will exhibit both a tendency to occur in sequences and a seasonal variation. Corrective coefficients have been introduced which serve to amend the probability estimates evaluated on the basis of assumed random distribution of events in order to make due allowance for such effects. The results have been presented in both tabular and graphical form.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Air Force Base, Va., October 27, 1961.

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TABLE I

CORRECTIVE FACTOR FOR COUPLING OF EVENTS

Year	One or more events for a mission duration of -			Two or more events for a mission duration of -
	5 days	10 days	15 days	10 days
1943				
1944				
1945				
1946	0.73	0.65	0.54	2.71
1947	.73	.68	.65	2.88
1948				
1949	.84	.83	.85	3.23
1950				
1951	.86	.71	.56	1.72
1952	.84	.82	.72	2.37
1953				
1954				
1955				
1956	1.04	1.06	.95	1.29
1957	.74	.68	.83	2.05
1958	1.06	1.07	1.18	.57
1959	.75	.83	.83	1.76
1960	.80	.90	.81	2.66
Mean values	0.84 (σ = 0.11)	0.82 (σ = 0.14)	0.79 (σ = 0.18)	2.12 (σ = 0.75)

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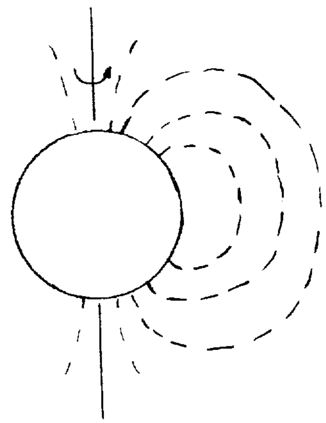
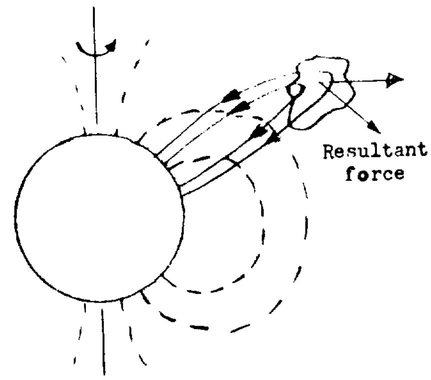
TABLE II

CORRECTIVE FACTORS $C_{s,f}$ AND $C_{s,u}$ FOR SEASONAL EFFECT

Solar cycle	$C_{s,f}$ (favorable months)	$C_{s,u}$ (unfavorable months)
1943 - 1954	0.68	1.65
1954 - 1960	0.62	1.77
Average	0.65	1.71

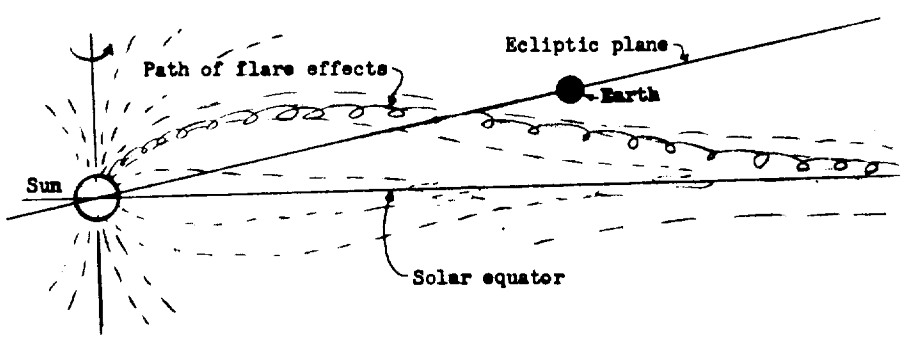


(a) Dipole magnetic field.



(b) Forces to which solar wind plasma is subject.

(c) Resultant background magnetic field of the sun.



(d) Solar flare effects.

Figure 1.- Origin of distorted solar magnetic field.

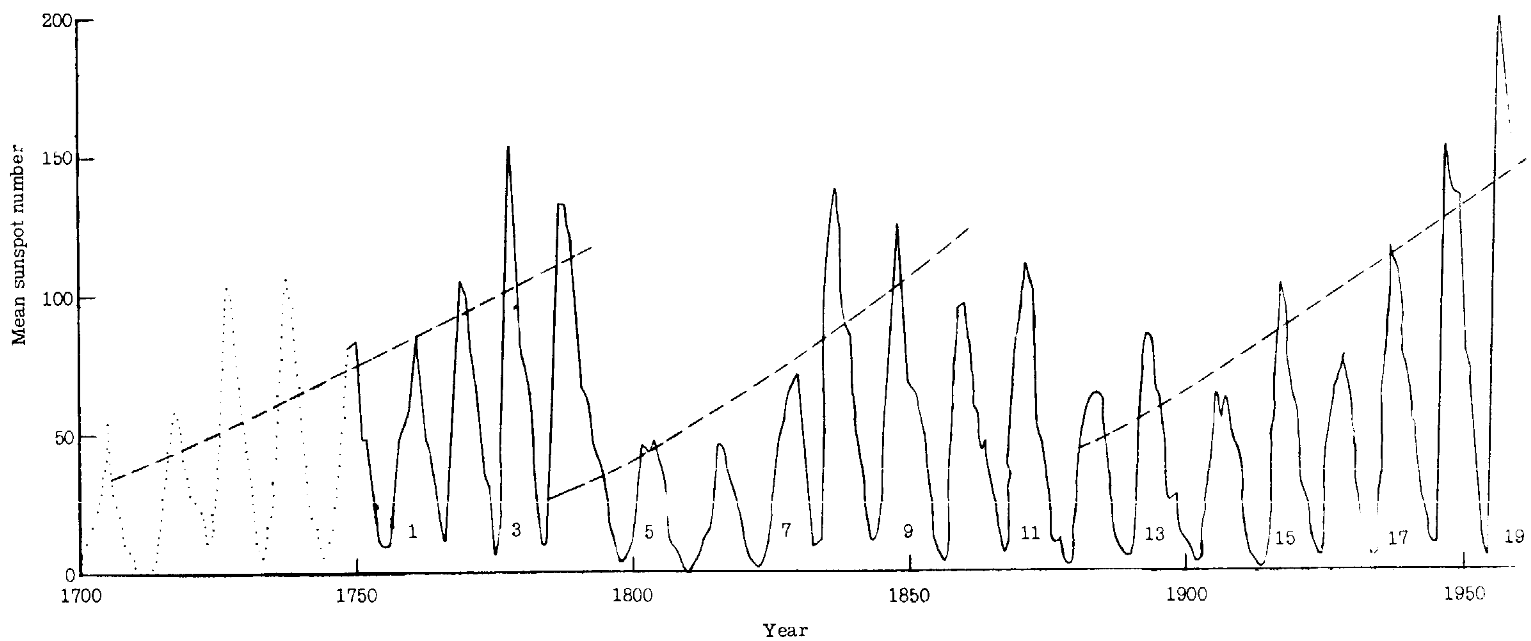


Figure 2.- Variation in mean sunspot numbers. (Zurich daily relative values; ref. 6.)

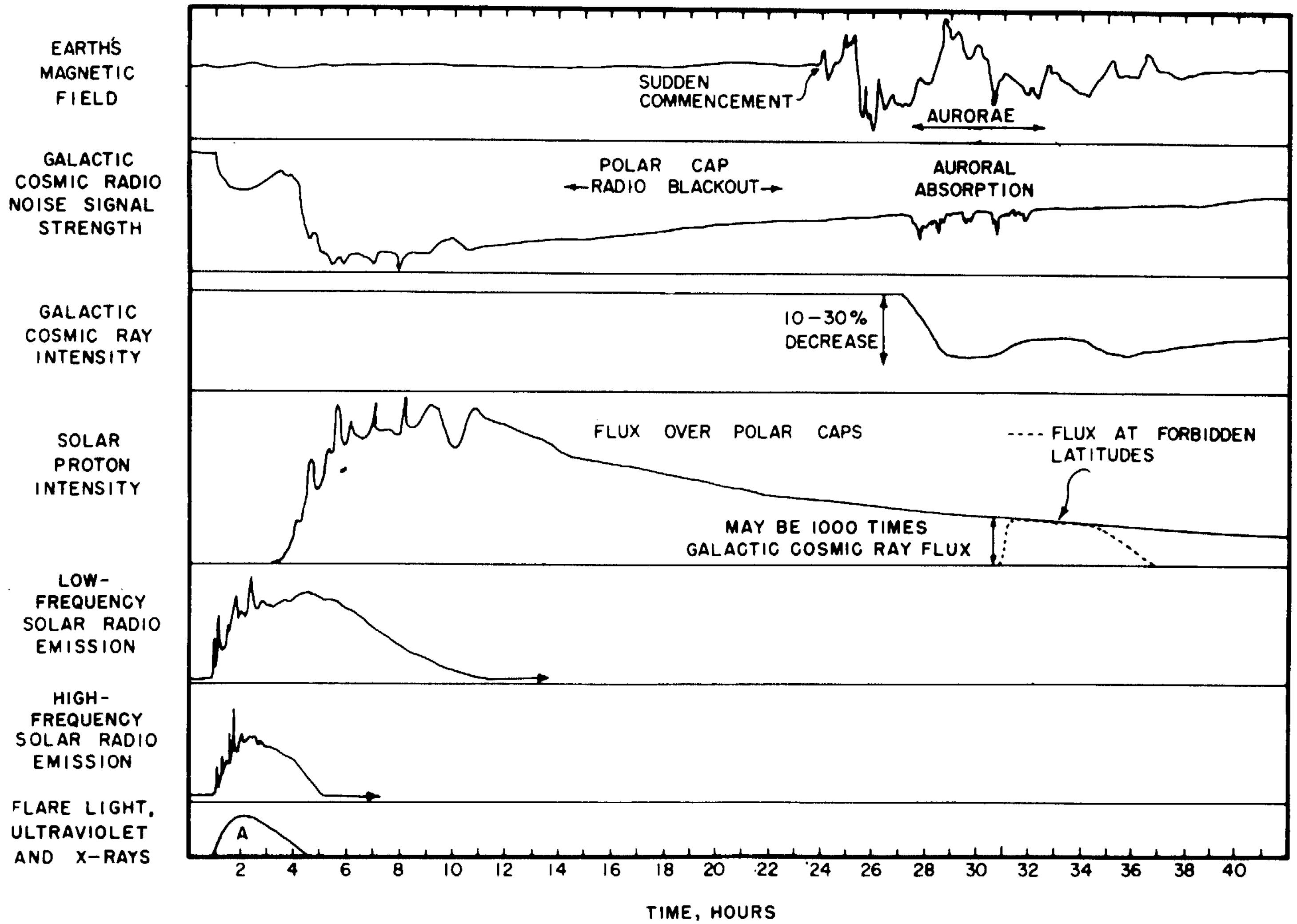


Figure 3.- Time sequence of most of the important chromospheric flare effects observable at the earth. (See ref. 2.)

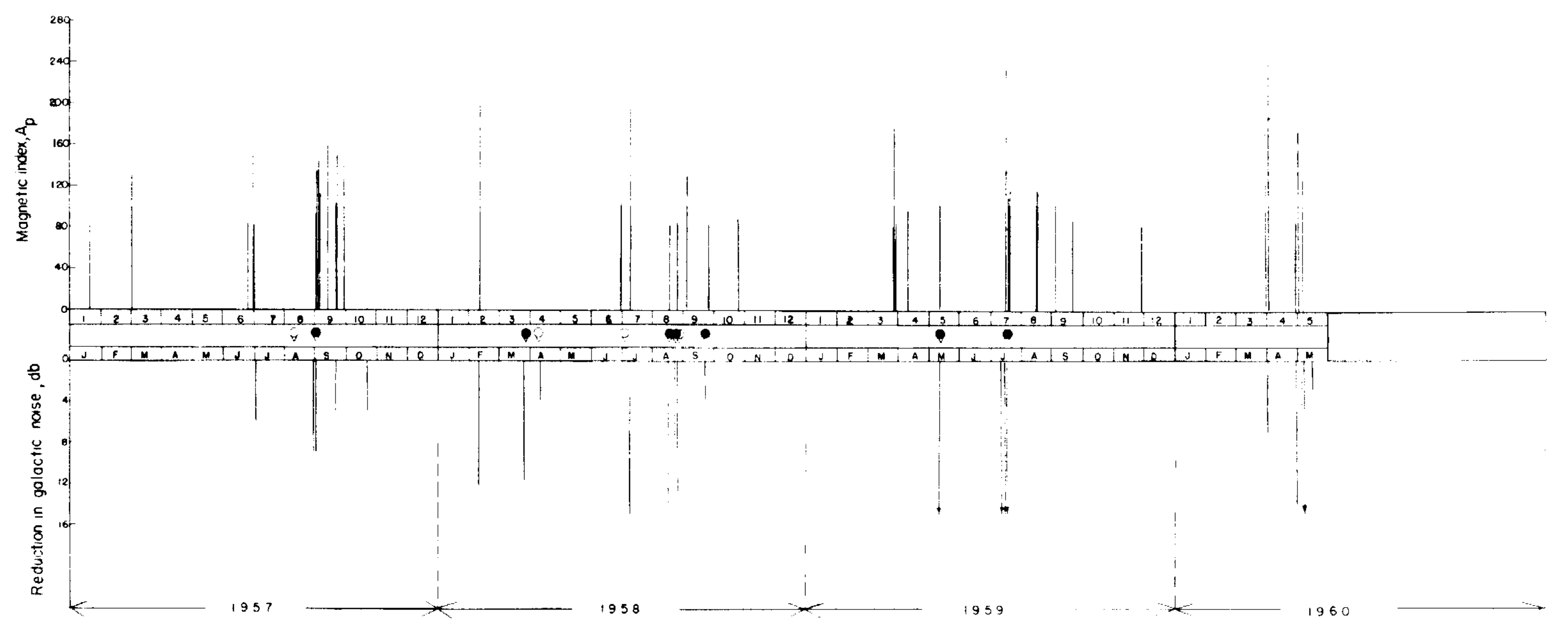


Figure 4.- Summary of balloon, riometry, and geomagnetic data obtained during International Geophysical Year.

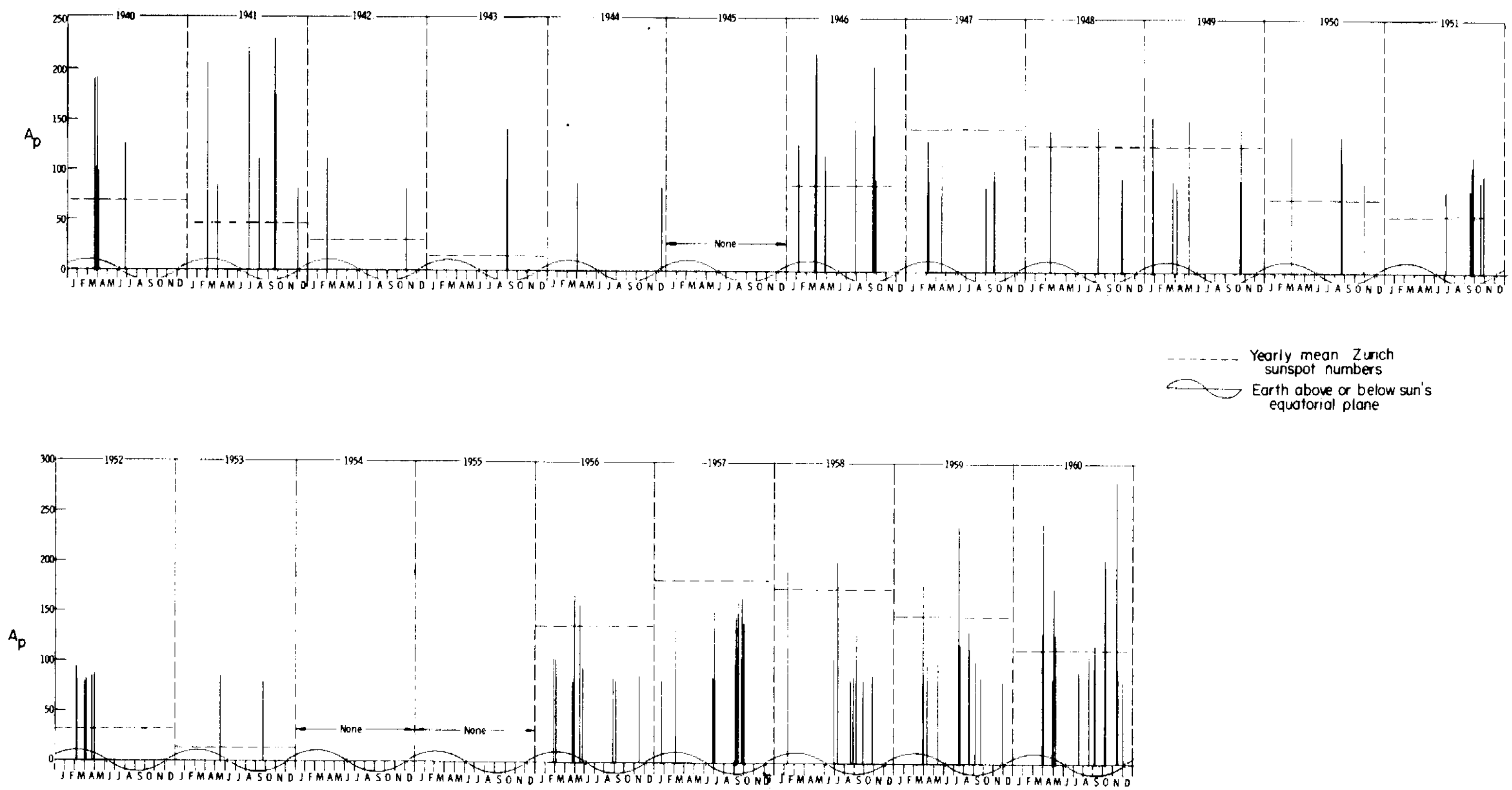


Figure 5.- Summary of intense geomagnetic storms from 1940 to 1960 (magnetic index $A_p > 80$).

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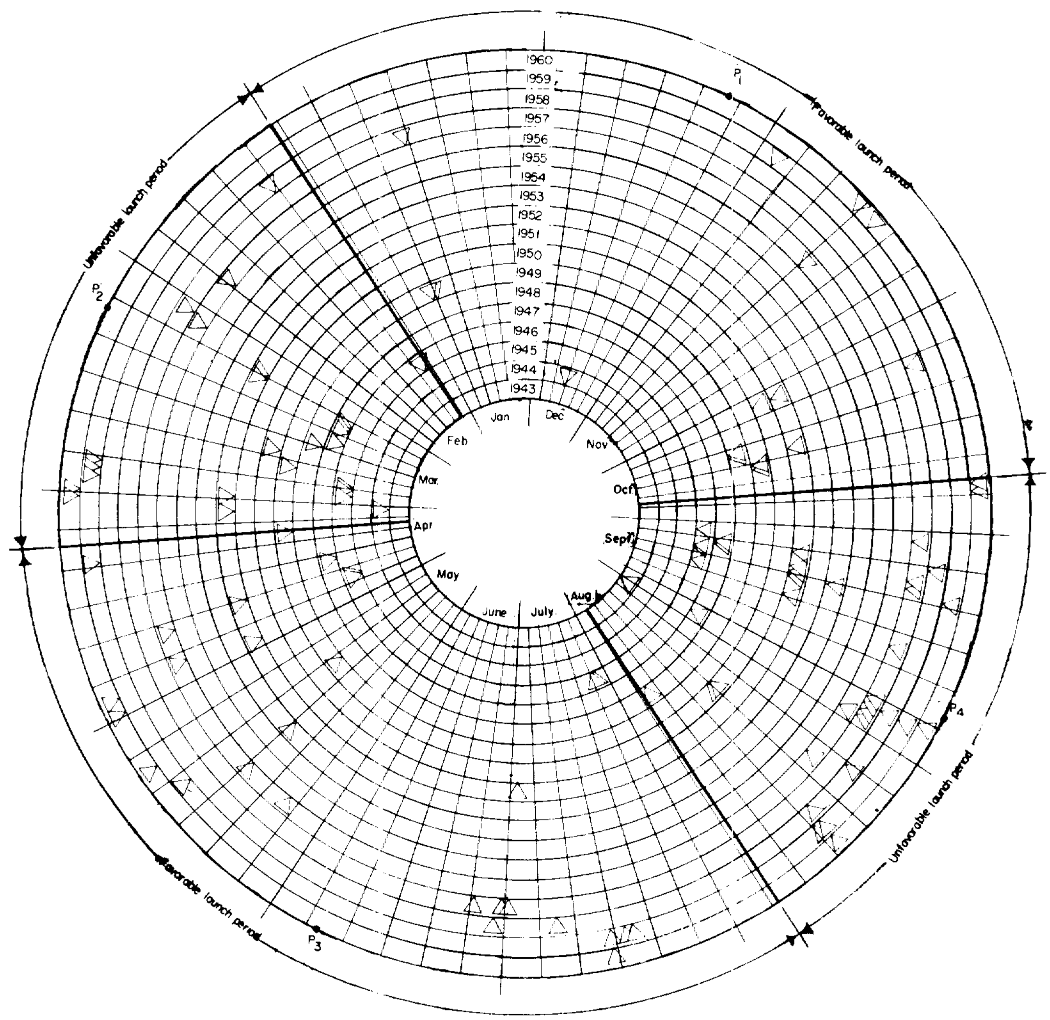
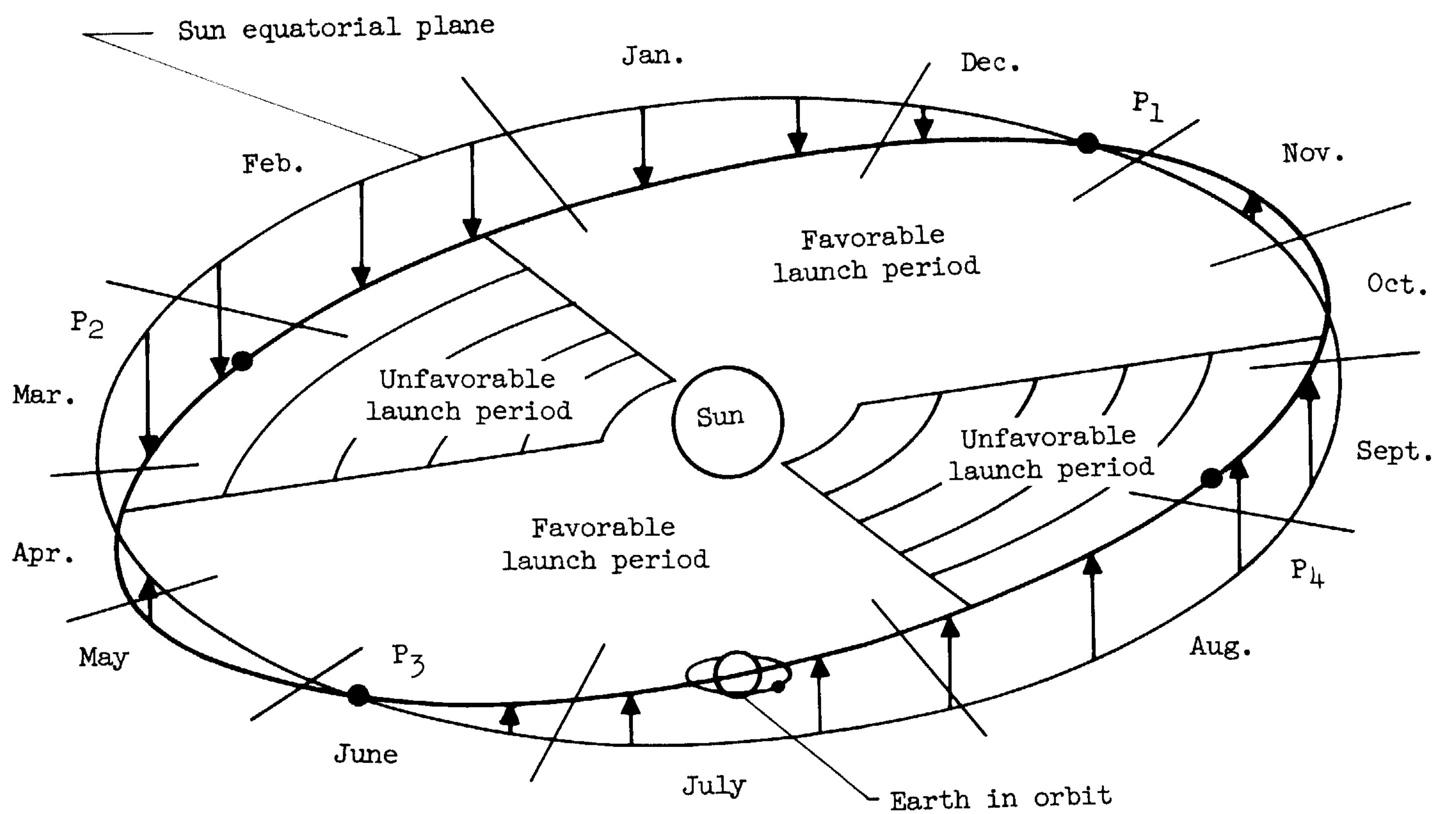


P_1 and P_3 earth crossing sun's equatorial plane
P_2 earth maximum distance south of sun's equatorial plane
P_4 earth maximum distance north of sun's equatorial plane

Figure 6.- Polar plot of intense geomagnetic events ($A_p > 80$) during 1943 to 1960 inclusive.



P_1 and P_3	Earth crossing sun's equatorial plane
P_2	Earth maximum distance south of equatorial plane
P_4	Earth maximum distance north of equatorial plane

Figure 7.- Motion of earth relative to sun's equatorial plane.

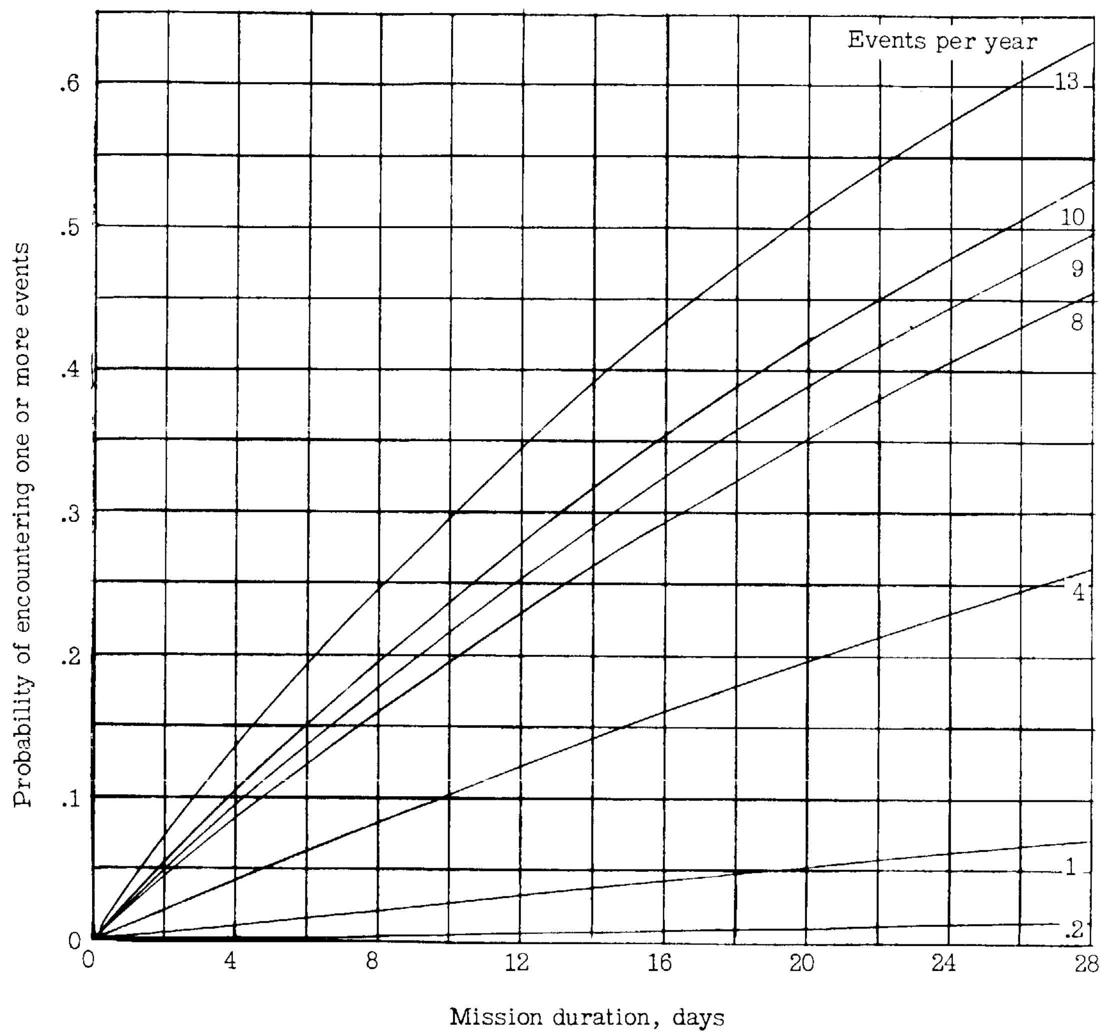
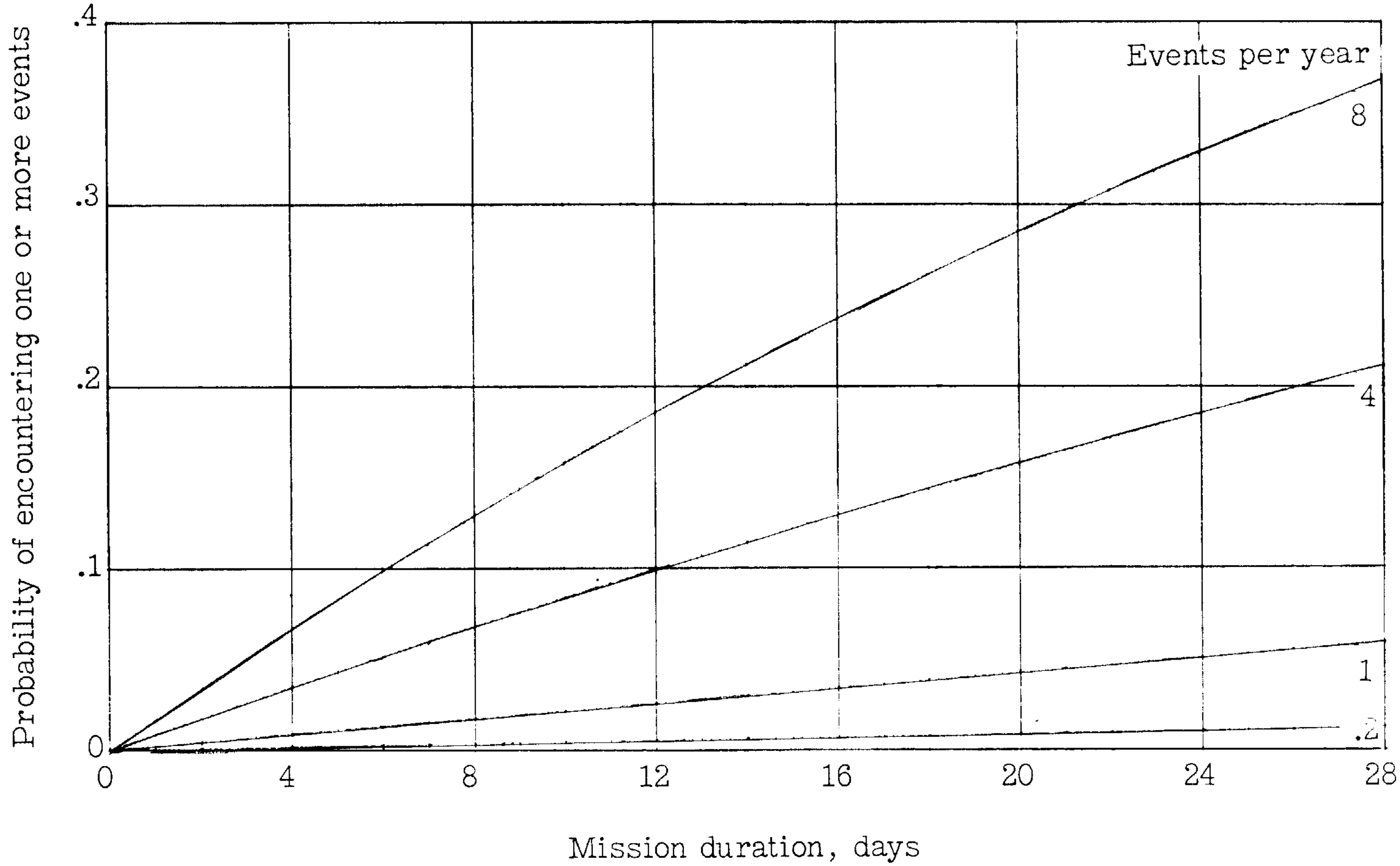


Figure 8.- Probability of encountering one or more events, for a given duration of mission, with the number of random events per year as parameter.



(a) Bunching effect.

Figure 9.- Bunching, seasonal, and combined effect on probability of encountering one or more events.

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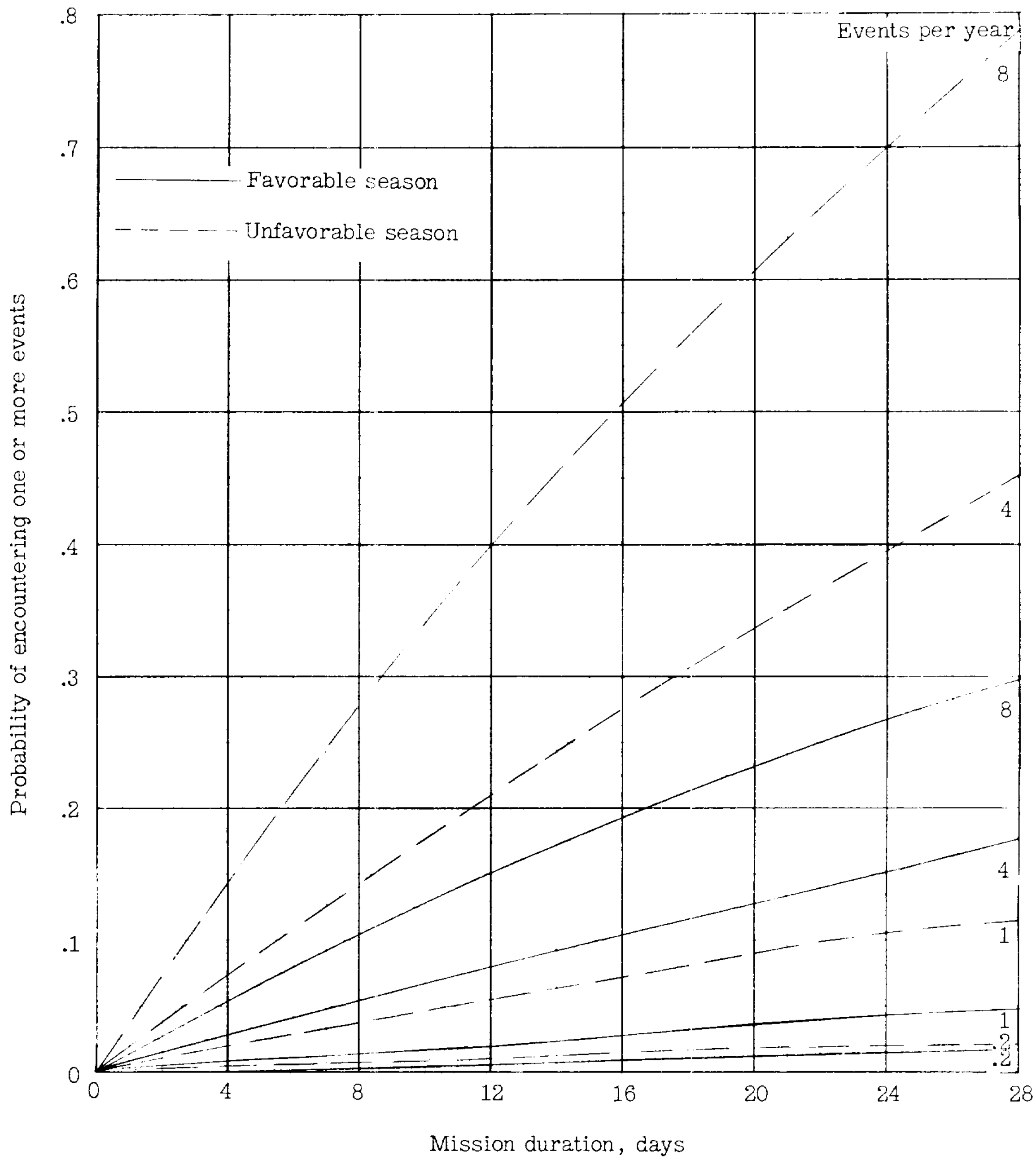
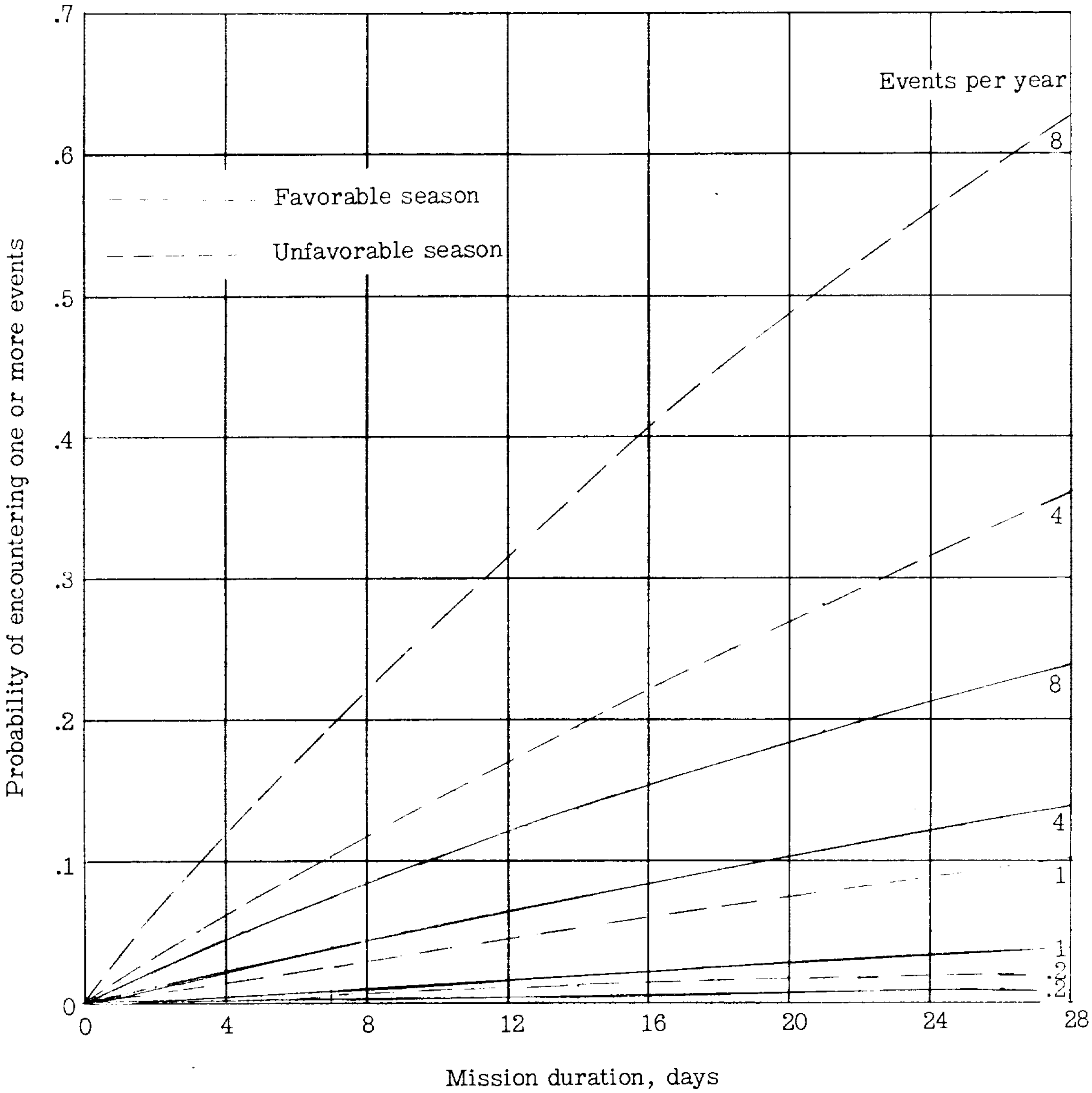


(b) Seasonal effect.

Figure 9.- Continued.



(c) Combined seasonal and bunching effect.

Figure 9.- Concluded.

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